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The rupture force of liquid bridges in two and three particle systems

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ABSTRACT

The measurement of the rupture force for an axially strained liquid bridge has been the subject of research for the last three decades and is fundamental to the understanding of the behavior of multiphase systems in granular materials. The study herein presents experimental work measuring the rupture force of pendular and capillary bridges in a three-particle configuration providing an axial and a shear strain. Results and subsequent analysis indicates that the rupture force and maximum rupture distance are the effect of surface characteristics, straining mechanism and effective liquid volume. For systems of more than two particles, we note that the effective packing fraction of the particles has a significant impact on the force required to rupture such a bridge.

1. Introduction

Investigating the phenomena involved in solid–liquid interactions is important due to the ubiquitous presence of compound solid–liquid systems among a variety of industries (i.e. pharmaceutical, chemical, cosmetic, and agricultural) and with diverse chemical and physical applications, such as agglomeration, and crystal growth. In these systems strong adhesion can result from the liquid meniscus that forms around the point of contact between solid surfaces [1]. This force is called the capillary force. In a two-particle system, these menisci bind solid surfaces by creating a bond between two finite contact points. The phenomenon of capillary adhesion is of great importance for granular materials and powders in the macroscale [2]. While the formation of agglomerates is commonplace in the industrial processing of solid mixtures, axial straining of a liquid bridge, in particular, can be evidenced in the granulation process.

Understanding and modeling multiphase systems is complex due to the different forces acting on the solids depending on the volume of fluid present. Depending on the liquid volume-capillary, surface and viscous forces can appear and change the mechanical properties of the mixture, such as its tensile strength [3–5]. The increasingly intricate interactions between the solid and liquid components, as the saturation level increases, has limited most of the available experimental studies to the pendular regime, and analytical models are developed for stable pairwise, axisymmetric bridges. Furthermore, the study of the formation and rupture of binding liquid networks has the added problem of bridge stability, particularly when dealing with bridges linking spherical solids. To forgo this problem most studies are limited to working with *small* liquid volumes (relative to particle size) such that a stable meniscus can be sustained between the solids [6,7]. A formal definition of what we consider to be small liquid volumes will be discussed later.

The attraction or repulsion forces between solids and the interstitial liquid are a result of a pressure differential across the interface. The pressure differential can be calculated using the Young–Laplace (YL) equation if the shape of the meniscus is known [2]. Megias-Algacil & Gauckler [8,9] recently presented a study for the capillary forces between spheres for liquid volumes forming both concave and convex liquid bridges. The results analyze the nature of the cohesive forces and present values for contact angle and relative liquid volume, defined as $V_{rel} = V/\left(\frac{4}{3}\pi R^3\right)$, for which a concave or convex meniscus can be expected. Urso et al. [10,11] present theoretical two-dimensional studies for the rupture of liquid bridges including the transitional states between pendular and capillary saturation level. They introduce equations to calculate the area of the liquid bridge surface for different saturation states and meniscus geometries. Murase et al. [12,13] presented a first attempt at characterizing the straining phenomena for a liquid bridges of different volumes held between three spheres both experimentally and computationally. They focused largely on the differences between dynamic and

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static pendular bridge forces and conclude that the maximum tensile force of the liquid bridge is the same for the two and three sphere system for a static rupture mechanism, but two times larger for the three-particle configuration under dynamic rupture conditions.

It is the objective of this study to perform experimental measures for the rupture force of menisci between two- and three-sphere interactions. We will follow the taxonomy described by Urso et al. [10,11], where bridges between two particles are termed pendular, systems where the particle interstices are fully saturated are called capillary, and intermediate saturations where there are varying degrees of interstitial voids are considered to represent funicular saturation. This work will measure both pendular and capillary rupture forces with a focus on the impact of bridge volume and particle symmetry effects.

1.1. The rupture of a pendular liquid bridge

The rupture force for pendular liquid bridges has been studied for decades [2,4,5,14-18]. Particle–plane and particle–particle interactions have been modeled for spherical particles and small liquid volumes. In general, the solution to the rupture energy of a liquid bridge can be found by considering it as a two-part problem. First, the stability problem and second, the net attraction/repulsion forces induced by the formation of liquid bridges [4].

When considering a packed bed, the theory for different saturation levels identifies the limit of the pendular regime at ≈13% moisture content, while the funicular regime is identified as corresponding to a moisture content above 13% and up to 25% [19]. It is known additionally, that for small enough volumes, where the effect of gravity can be neglected, the mean curvature of the bridge surface between two spheres may be approximated as constant and the contact point is fixed [20]. The maximum volume of fluid, for which the effects of gravity can be considered negligible, is estimated using the following equation:

$$\kappa = \sqrt{\frac{\sigma}{g\rho}}, \tag{1}$$

where ρ_l is the density difference between the solid and the liquid phases, and κ is known as the capillary constant, or capillary length.

In order to model such interactions it is necessary to solve the Young–Laplace (YL) equation for capillary forces in the presence of a curved liquid-vapor interface. The pressure differential across the liquid-gas interface, is defined by the shape of the meniscus. It is commonplace to assume the shape of the meniscus is described by a solid of revolution [21]. While numerical solutions for the YL equation for a wide variety of revolution surfaces are known, more often than not, an equation based on a toroidal shape is implemented [7,22,23]. Based on this approach, in order to perform an axially oriented force balance, first a system in equilibrium is defined (Fig. 1). Then, making use of the surfaces of revolution to calculate the pressure differential across the liquid–gas interface according to YL, one employs the theories of capillarity and lubrication to calculate the total cohesive force [24,25].

The work discussed herein follows the procedure described by Pitois et al. for the rupture energy of a pendular liquid bridge [24]. The simplified dimensionless expression derived for the capillary force contribution takes the form

$$F^*_{cap} = \frac{F_{cap}}{\sigma R} = 2\pi \cos\phi \zeta_v, \tag{2}$$

with,

$$\zeta_v = 1 - \left(1 + \frac{(2V^*)}{(\pi D^{*2})}\right)^{\frac{-1}{2}}, \tag{3}$$

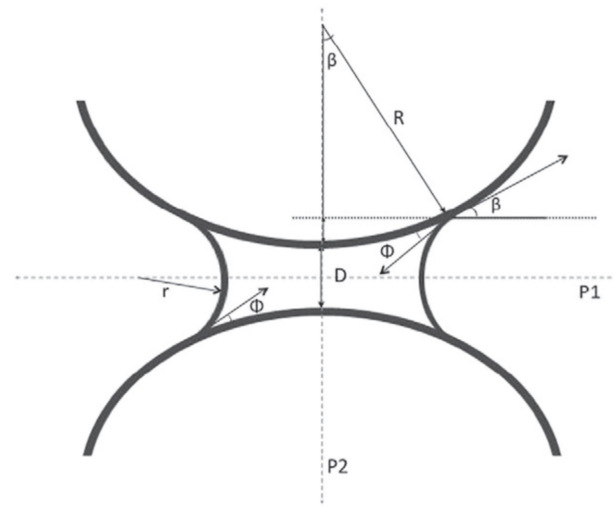

Fig. 1. Sketch of a liquid bridge formed between two spheres. P1 and P2 are planes of symmetry.

where D is the distance between the two solid surfaces, σ is the fluid surface tension, and ϕ is the solid-liquid wetting angle. The star symbol (*) denotes the dimensionless form of an expression. The length scale to write dimensionless parameters is the radius of the sphere R, such that $V^* = V/R^3$, $D^* = D/R$. Similarly, we use as the force scale σR (see Eq. (2)).

1.2. Viscous forces

An expression for the viscous force contributions to granular systems was developed by Ennis et al. based on a derivation of the Reynolds equation to describe thin film behavior [7]. The function revealed how the contribution of lubrication forces to the total rupture force becomes increasingly important for high viscosity fluids. While the objective of the current work is focused on low viscosity fluids only, we have implemented the viscous contribution as part of the computational model for completion. The viscous contribution, in its dimensionless form, can be written as:

$$F^*_{visc} = \frac{3}{2}\pi \frac{C_a}{D^*} \zeta_{v^2} \tag{4}$$

where, Ca is the capillary number defined as $C_a = \mu\sigma/a$, and μ is the viscosity of the fluid. It follows that the total (dynamic) force is the sum of the capillary and viscous terms. A relationship between the liquid bridge volume, the liquid–solid contact angle and the quasi-static rupture distance, was presented by Lian et al. [22] for liquid volumes where the effect of gravity can be neglected. Their rupture distance can be written as:

$$D^*_{rupt} \simeq \left(1 + \frac{\phi}{2}\right) V^{*\,1/3}. \tag{5}$$

The total liquid bridge force contribution can then be expressed as:

$$F^*_{tot} = 2\pi \cos\phi \zeta_v + \frac{3}{2}\pi \frac{C_a}{D^*} \zeta_v^2 \tag{6}$$

Key contributors to viscous forces, such as wetting angles, and stability on curved surfaces have become areas of independent studies [26–28]. Results indicated that minimal shifts in the shape of the meniscus had a significant impact on the evolution and rupture of the bridge. The present work will be concerned with steady state, non-thermodynamic equilibrium, and will assume the bridge